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SHOCK PHENOMENA IN COOL STAR ENVELOPES

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Disks and Winds in Young Stars

a) Wind-Disk interactions

The most plausible source for the near-infrared excess emission observed in pre-main sequence stars is a circumstellar disk (Lynden-Bell and Pringle 1974; Rucinski 1985; Adams, Lada, and Shu 1987). The ubiquity of IR excesses suggests that disks are quite common in early stellar evolution. The general absence of infrared disk emission from main sequence stars suggests that most disk material eventually either falls onto the central star, forms planets, or is otherwise dispersed, perhaps by the impact of high-velocity stellar winds.

Although theoretical arguments and observational constraints indicate that typical pre-main sequence disks should be relatively flat, on quite general grounds one expects the disk to become proportionately thicker at larger radii (e.g., Kenyon and Hartmann 1987). Under these circumstances a radially-directed, near-equatorial wind from the central star will strike the disk obliquely. The winds from T Tauri stars are highly supersonic (Kuhi 1964), and so even very oblique impacts can produce significant shock heating and observable emission from the wind.

The broad, blue-shifted optical [O I] and [S II] emission in T Tauri stars has been attributed to disk occultation of a stellar wind at distances ~ 100 A.U. (Jankovics, Appenzeller, and Krautter 1983, hereafter JAK; Appenzeller, Jankovics, and Ostreicher 1984, hereafter AJO; Edwards et al. 1987). We have suggested (Hartmann and Raymond 1988) that this [O I] and [S II] emission is the observational signature of the oblique shocking of stellar wind against the circumstellar disk.

We were led to this model by the difficulty of producing the emission directly in the stellar wind. To show these problems, we followed an element of gas in a radially-expanding

stellar wind as it cools and recombines. The cooling, ionization evolution, and emission spectrum are computed by codes developed for interstellar shock waves, with current atomic rates summarized in Cox and Raymond (1985) and some modifications for high densities discussed in Mauche and Raymond (1987). Of particular importance for the T Tauri wind models are low temperature dielectronic recombination (Nussbaumer and Storey 1983), charge transfer (Butler and Dalgarno 1980), and Auger ionization by X-ray photoionization of the K shells of carbon, nitrogen, and oxygen.

Figure 1 shows the time evolution of the temperature and cooling rate for an element of gas in the $10^{-8} M_{\odot} \text{yr}^{-1}$ model with the X-ray fluxes reduced by a factor of 10. The variation of quantities with radial distance in the wind can be found by simply multiplying the time by 200 km s^{-1} . The cooling coefficients are in units of $10^{-23} \text{ erg cm}^3 \text{s}^{-1}$, and must be multiplied by the product of electron and hydrogen densities $N_e N_H$ to calculate the emission per cm^3 per second. Photoelectric heating is negligible until the gas begins to recombine at a time of 10^3 s. The heating rises steeply until it balances radiative cooling in the plateau region between 1 and 2×10^3 s. Beyond that time the radiative cooling drops and adiabatic expansion cooling dominates. The apparent rise in adiabatic cooling at large times reflects a decrease in N_e , and the adiabatic cooling rate per cm^3 actually decreases with temperature.

The wind models fail to reproduce the observations because radiative losses and adiabatic expansion cool the wind to temperatures below 1000 K at radii ≤ 0.2 A.U. At these distances wind densities are very large, resulting in unacceptable collisional de-excitation of [S II]. It is conceivable that the wind does not expand spherically, so that adiabatic cooling is less important. However, in that case the gas density does not fall off as r^{-2} , so that it is even more difficult to reach low enough densities to produce strong [S II]. Furthermore, the observations indicate a large line-of-sight velocity dispersion, which would be difficult to obtain without appreciable divergence in the flow.

Our results indicate that T Tauri winds must be heated at large distances from the star to produce the observed [S II] emission. A shock between the wind and the disk is an attractive mechanism to produce this heating, since in a radial wind the disk becomes thick enough to produce significant shock velocities only at large radii. We constructed a quantitative model of a disk and of the interaction between the disk surface and the stellar wind following the ideas of Canto (1980). In this scheme, the following regions are present (Figure 2): (1) the unshocked stellar wind; (2a) a flow region containing gas cooling down from passage through an oblique shock; (2b) a flow region in which the gas has cooled down and is joined by other previously-shocked stellar wind material sliding along the surface of the external medium; and (3) undisturbed ambient medium. We made the simplifying assumptions that the emission comes from the cooling region (2b), and that this cooling region is so thin that its shape is given essentially by the shock surface separating (1) and (2b). We further assume that the radiating gas has cooled and compressed enough that its velocity perpendicular to the local shock surface is negligible, and thus its motion is entirely parallel to the shock surface at a speed given by momentum conservation across the shock (Canto 1980).

We applied this theory to a simple disk model. We assumed that the disk has a uniform surface density of 12.5 g cm^{-2} and a radial extent 100 A.U. (and therefore mass $0.044 M_{\odot}$), and a temperature distribution of $T = 550 (r/1\text{A.U.})^{-1/2}$, corresponding to simple radiative equilibrium for disk material around a star of effective temperature 4000K and radius $4 R_{\odot}$. We assume a stellar mass of $0.8 M_{\odot}$. The wind is assumed to have a mass loss rate of $10^{-7} M_{\odot} \text{ yr}^{-1}$, with a terminal velocity of 200 km s^{-1} .

The results are shown in Figures 3 - 5 and in Table 1. In general, the shape of the wind-disk shock surface is not very sensitive to the surface density σ or to M or v_w . The reason is that the shock surface occurs about 4 scale heights above the midplane in this model, where the disk density varies very rapidly, so modest changes in ram pressure produce small

changes in the height of the shock surface. The resulting forbidden-line fluxes are sensitive to the shape of the shock surface and also to the assumed initial wind velocity, because the shocks are so oblique. In addition, lower mass loss rates produce less emission; a model with $M = 10^{-8} M_{\odot} \text{ yr}^{-1}$ and the other parameters unchanged produces about 10 times less [O I] emission and about 5 times less [SII] emission.

The wind-disk shock results exhibit several encouraging features. Low-excitation emission is produced, in reasonable agreement with observed line ratios. The [O I] and [S II] profiles are in reasonable agreement with the observations of Edwards et al. (1987).

While the wind-disk shock model accounts for a number of qualitative features of the observations, there are problems with it as well. The principal difficulty is that the predicted luminosities of [O I] and [S II] are a factor of 3 - 10 times smaller than observed. We think that our simple shock models underestimated the actual emission produced for a given external pressure distribution. The oblique shock surface of our model is subject to Kelvin-Helmholtz and shock instabilities (Elmegreen 1978). Since the shocks are so oblique, any slight perturbation which tilts the surface normal toward the star will result in a much larger ram pressure by the wind, driving the shock deeper into the disk and tilting the surface still more. Thus, the instabilities inherent in the problem are almost certain to produce shocks that are less oblique, and hence have higher shock velocities, than predicted by the equilibrium model. Increasing shock velocities from ~ 25 to $\sim 35 \text{ km s}^{-1}$ in the above model would increase the line emission fluxes by a factor of two to three, producing better agreement between model and observation.

The disk thickness is also an important parameter in our model. An opaque disk whose surface is similar to that of the model in Figure 3 would obscure half of the sky as seen from the star. This implies that, if all TTS had such disks, half of them should be so obscured as to be detectable only at infrared wavelengths. IRAS surveys have turned up some embedded

sources, but not nearly enough (Myers et al. 1987; Beichman et al. 1983). Thus the wind-disk interface of the model in Figure 3 cannot be the photospheric surface of the disk.

We suggest that this problem can be avoided if the dust settles toward the disk midplane, as is generally expected to occur on fairly short timescales (Weidenschilling 1980, 1984). This is especially plausible as the wind-disk interaction surface typically occurs several scale heights above the midplane. For example, in the model discussed above, at $R = 72.1$ A.U. the shock surface is at $z = 49.56$ A.U., which is 4.16 local scale heights above the midplane. Thus the wind shocks far above the disk, in its tenuous outer atmosphere. It seems quite plausible that dust would settle out from such heights quite quickly.

Thus we envisage a situation where the upper one or two scale heights of the disk are relatively warm, since they are easily heated by the star, and the scale height of this material may be quite significant; the bulk of the dusty disk resides near the midplane, with likely smaller characteristic scale height.

The wind-disk shock model for the forbidden-line radiation makes several observational predictions. One of the most important predictions is that stars with higher wind velocities should generally produce larger shock velocities and thus higher-excitation spectra. It is interesting that HL Tau, the only object in the Edwards et al. (1987) sample with fairly strong [N II], has a wind velocity of at least 400 km s^{-1} , a factor of 1.5 to 2 times larger than the velocity widths observed for the other stars. Scaling the above basic model for a higher wind velocity, one finds shock velocities of $40 - 50 \text{ km s}^{-1}$, in the range needed to produce [N II].

It is difficult to heat the wind at large distances by stellar energy fluxes. On the other hand, it is difficult to make the disk sufficiently thick close to the star without assuming unreasonably large temperatures. Therefore, direct spatial resolution of emitting regions of ~ 50 A.U. in extent will strongly support the wind-disk shock interaction model. A radius of 50 A.U. at 160 pc corresponds to an angular diameter of $2/3''$, which can in principle be observed

from the ground in good seeing or through speckle interferometry, and can be detected with HST. (The electron densities estimated by Edwards et al. [1987] also imply such large emitting volumes.)

If spectra with sufficient spatial resolution can be obtained, one can look for the characteristic position-velocity profile of the model. Viewed pole-on, the wind-disk shock model predicts that the most negative radial velocity material will be seen at the periphery of the forbidden-line emission. The latitude-dependent wind model of Edwards et al. (1987) predicts the reverse.

As shown in the previous section, the disk-wind mechanism requires an extended, optically-thin upper disk envelope. Thus the connection between the shock surface and the disk photosphere, where light from the central star is reprocessed, is indirect. Nevertheless, one expects that stars with larger infrared excesses due to reprocessing should generally have thicker disk envelopes and thus more wind-disk shock emission. There does seem to be some evidence for such a correlation. In the survey of Taurus-Auriga by Strom et al. (1988), 15 of the 18 stars with infrared luminosities ≥ 0.5 times the stellar luminosity have [O I] equivalent widths $\geq 1 \text{ \AA}$; conversely, only 5 of the 38 stars with $L_{\text{IR}} \leq 0.5 L_*$ have such [O I] emission. Of course, broad [O I] emission in a star without IR excess, and hence without a circumstellar disk (Adams, Lada, and Shu 1987; KH), would be hard to explain by a wind-disk shock.

The model predicts that some TTS should be viewed through a gaseous envelope of density $\sim 10^7 \text{ cm}^{-3}$ and column densities $\sim 10^{22} - 10^{23} \text{ cm}^{-2}$. Thus one might find excess "interstellar" absorption in lines like Ca II, Mg II, Na I, without the consequent dust absorption (since the dust has presumably settled closer to the midplane).

One of the implications of our model is that some T Tauri stars eject a lot of mass near the equatorial plane, the exact opposite of a "jet" model. This does not rule out the presence of jets, but does emphasize the importance of near-equatorial flow. It is likely that the near-

equator flow is more efficient in removing angular momentum than a jet along the rotation axis. Since T Tauri stars are generally slow rotators (Bouvier et al. 1986; Hartmann et al. 1986), the ejection traced by [O I] emission may play an important role in early stellar evolution.

b) T Tauri stars

The low-mass, pre-main sequence T Tauri stars exhibit large excesses of infrared emission from warm dust grains ($T \sim 100$ K to 1500 K). This dust must extend close to the star to explain the high dust temperatures and have a large radial extent to produce a range of temperatures, yet there must be relatively clear lines of sight to the stellar photospheres of these objects. A simple way to deal with the observations is to assume that the dust is in a disk around the young star rather than a series of spherical shells. Several other lines of evidence indicate that most young stars are surrounded by dusty disks, including direct observations of extended emission (Beckwith *et al.* 1984; Grasdalen *et al.* 1984). The general blue-shift of forbidden line emission in many young stars has been attributed to occultation of receding material by an opaque disk (Appenzeller, Jankovics, and Ostreicher 1984), and bipolar flow models satisfactorily account for the observed line profiles (Edwards *et al.* 1987).

Adams and Shu (1986) pointed out that a flat, dusty disk will absorb and reprocess ~ 25% of the photons emitted by the central star, and Adams, Lada, and Shu (1987) later applied this idea to explain the infrared (IR) energy distributions of pre-main sequence stars. Adams, Lada, and Shu noted that the observed IR excesses are considerably larger than 25% of the stellar flux, suggesting that some of the excess might be produced by a flow of material through the disk (i.e., accretion).

We have analyzed spectral energy distributions of T Tauri stars to place limits on the amount of accretion which might occur during this early phase of stellar evolution (Kenyon and Hartmann 1987). The typical system has a far-IR energy distribution which follows $\lambda F_\lambda \propto$

$\lambda^{-0.7}$, while the flat disk model predicts $\lambda F_\lambda \propto \lambda^{-1.3}$. If the height of the disk photosphere increases faster than linearly with radius (i.e., the disk "flares"), then the energy distribution of a typical T Tauri star will be flatter than $\lambda F_\lambda \propto \lambda^{-1.3}$ because disk annuli at large radii from the central star can absorb more photons. A physically plausible amount of flaring results in an energy distribution which matches the observations of the typical system. An extreme amount of flaring can reproduce the energy distributions of those T Tauri stars with "flat spectra", $\lambda F_\lambda \sim \text{constant}$, but such disks probably are not physically plausible.

It is possible that source confusion in the long wavelength *IRAS* observations and uncertainties in the extinction correction may help to explain the observed IR energy distributions of these unusual T Tauri stars.

If most T Tauri stars have disks close to the stellar surface, then it is plausible that some of this material falls onto the central star. The most promising candidates for accreting T Tauri stars are the so-called continuum stars, in which the stellar photosphere is veiled by a blue continuum source. In the accretion picture, the source of the blue veiling is the boundary layer, where disk material falls onto the stellar photosphere. An alternative source of blue veiling is a very active stellar chromosphere. The relative importance of accretion and solar-type chromospheric activity is difficult to assess in most T Tauri stars, given the primitive nature of boundary layer and chromosphere models. In the continuum stars, the luminosity of the blue veiling exceeds that of the stellar photosphere and it is unlikely that a chromosphere can be responsible for the observed luminosity. Simple boundary layer models can explain the observations of these objects if the accretion rate is \sim a few $\times 10^{-7} M_\odot \text{ yr}^{-1}$. We estimate that the lifetime of this phase is $\sim 10^5$ yr, so a small amount of material is added to a pre-main sequence star during its lifetime.

c) *T Tauri winds*

T Tauri stars also exhibit very intense spectral line emission, with luminosities totalling up to 10% or more of the total observed radiation (Cohen and Kuhi 1979; Calvet 1983). The observations suggest that the velocity field near the star (where the higher Balmer series and Na D lines are formed) may be quite complicated, but that outflow dominates beyond $\sim 2 R_*$ (where H α , Ca II, and Mg II are formed) for almost all T Tauri stars (see Hartmann 1985 for further discussion).

Estimates of T Tauri mass fluxes are of interest both for their implications for stellar physics as well as for estimates of the impact of stellar ejecta on the interstellar medium. We are in the process of constructing a grid of wind models for T Tauri stars in collaboration with Dr. N. Calvet of CIDA (Venezuela). These empirical wind models are isothermal and spherically symmetric. By calculating the emission line fluxes and profiles produced by a grid of models spanning a substantial range in temperature and mass loss rate, we will be able to place limits on atmospheric properties, and to infer the probable locations of formation for various types of lines. Our strategy is to calculate the radiative transfer and statistical equilibrium results for H, He I, Ca II, Mg II, and Na I model atoms in great detail for a few atmospheric models, and then use approximate techniques to scale the results to cover a much wider range of parameter space. The Pandora code has been modified to permit the use of Sobolev escape probabilities, which we use to rapidly calculate approximate models over a range of temperature and M .

The large emission line widths observed in T Tauri stars require large expansion velocities, large turbulent velocities, or a combination of both. We find the best match to H α line profiles for models in which the turbulent velocity dominates close to the star, while expansion dominates farther out, a qualitative prediction of the Alfvén wave model for mass loss (DeCampli 1981; Hartmann, Edwards, and Avrett 1982). We have been able to verify the result of Hartmann, Edwards, and Avrett (1982) that the large H α /H β ratios seen in many T

Tauri stars require formation of H α in an extended region. This is easier to accomplish if turbulent velocities are significant (that is, lower mass loss rates are required, as originally suggested by DeCampli (1981)). We find that simple static, spherically extended models using large turbulent velocities overestimate the H α flux in a typical model by a factor of two or three in comparison with detailed moving source function calculations. The Sobolev method, which assumes negligible turbulent broadening in the source function solution, underestimates the H α flux by a similar factor. Thus, the H α flux is extremely sensitive to assumptions concerning the velocity field in the outer envelope. Lines formed closer to the star are less sensitive to the outer velocity field, and so we can use the Sobolev results to scale things rapidly with more assurance.

While we find that H α must be formed in the outer wind of strong-emission T Tauri stars, the wind models generally do not produce enough Ca II and Mg II emission (although the absorption components are in reasonable agreement with observation). Thus it seems clear that H α is a good wind indicator, while Ca II and Mg II resonance line fluxes indicate emission from a chromosphere at the base of the wind (cf. Calvet, Basri, and Kuhi 1984).

Calvet (1985) showed that the He I λ 5876 emission fluxes were difficult to understand in terms of recombination following X-ray photoionization. Some of our wind models indicate significant opacity in this line, suggesting that He I may become an important indicator of wind properties along with H α .

While most of our initial results are consistent with mass loss rates $\sim 10^{-8} M_{\odot} \text{yr}^{-1}$, some objects exhibit appreciable blue-shifted Na I absorption (and emission). Our models indicate that mass loss rates in excess of $10^{-7} M_{\odot} \text{yr}^{-1}$ will be required to account for these features. An additional prediction of the models is that the strength of the blue-shifted Na features should be correlated with the height of the Balmer emission jump. This is of considerable interest, since the objects with Na I absorption are generally peculiar strong-emission or

continuum stars. Mass loss rates this large are difficult to achieve with the stellar Alfvén-wave mechanism (cf. DeCampli 1981). As discussed below, we suspect that the strong-emission stars are accreting material at substantial rates from a disk, and that the ultraviolet continuum arises from boundary-layer emission. This accretion might provide enough energy to power the massive flows required to account for the Na I absorption. We have argued elsewhere (Hartmann and Kenyon 1985, 1987) that the FU Orionis objects are accreting luminous disks surrounding T Tauri stars. FU Ori objects also have strong blueshifted Na I absorption, and we argued that this material represents a wind coming off the disk surface. The same thing might be happening in the strong-emission T Tauri stars on a smaller scale.

In the next six months we intend to complete the grid of T Tauri wind models, with calculations for three or four mass loss rates at three isothermal temperatures, as well as some non-isothermal wind models which use the grid results to point to the best compromise overall temperature distribution. From these results we should be able to make mass loss rates estimates that are far more quantitative than ever before.

We have obtained spectrophotometry and simultaneous echelle observations of the Na I emission lines of a sample of bright T Tauri stars. Over the next six months, we will make detailed comparisons between the model grids and the observations. This analysis will allow us to test the idea that a disk wind is responsible for the emission features in the continuum T Tauri stars.

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Hartmann, L., and Raymond, J.C. "Wind-Disk Shocks Around T Tauri Stars," *Ap. J.*, submitted (1988).

TABLE 1
FLUXES AND LINE RATIOS
FOR WIND-DISK SHOCK MODEL

Line	Luminosity ^a	Ratio ^b
Basic Model		
[O I]	1.5E+29	100
[O II]	3.0E+27	2
[N II]	1.6E+27	1
[S II] $\lambda 6717$	2.6E+28	18
[S II] $\lambda 6731$	4.3E+28	29
[C I]	3.5E+29	233
Model with Centrifugal Correction		
[O I]	8.9E+28	100
[O II]	1.7E+27	2
[N II]	7.1E+26	1
[S II] $\lambda 6717$	2.3E+28	26
[S II] $\lambda 6731$	3.2E+28	36
[C I]	2.6E+29	294

^a In units of erg s⁻¹.

^b Ratio to [O I] = 100.

Figure 1- Time evolution of an expanding parcel of gas for the $10^{-8} M_{\odot} \text{ yr}^{-1}$ model. The vertical axis is in units of $\log(T/10^4 \text{ K})$ for the temperature (solid curve), while units of $\log(10^{-23} \text{ erg cm}^3)$ are used for the radiative and adiabatic cooling rates (dotted and dashed curves).

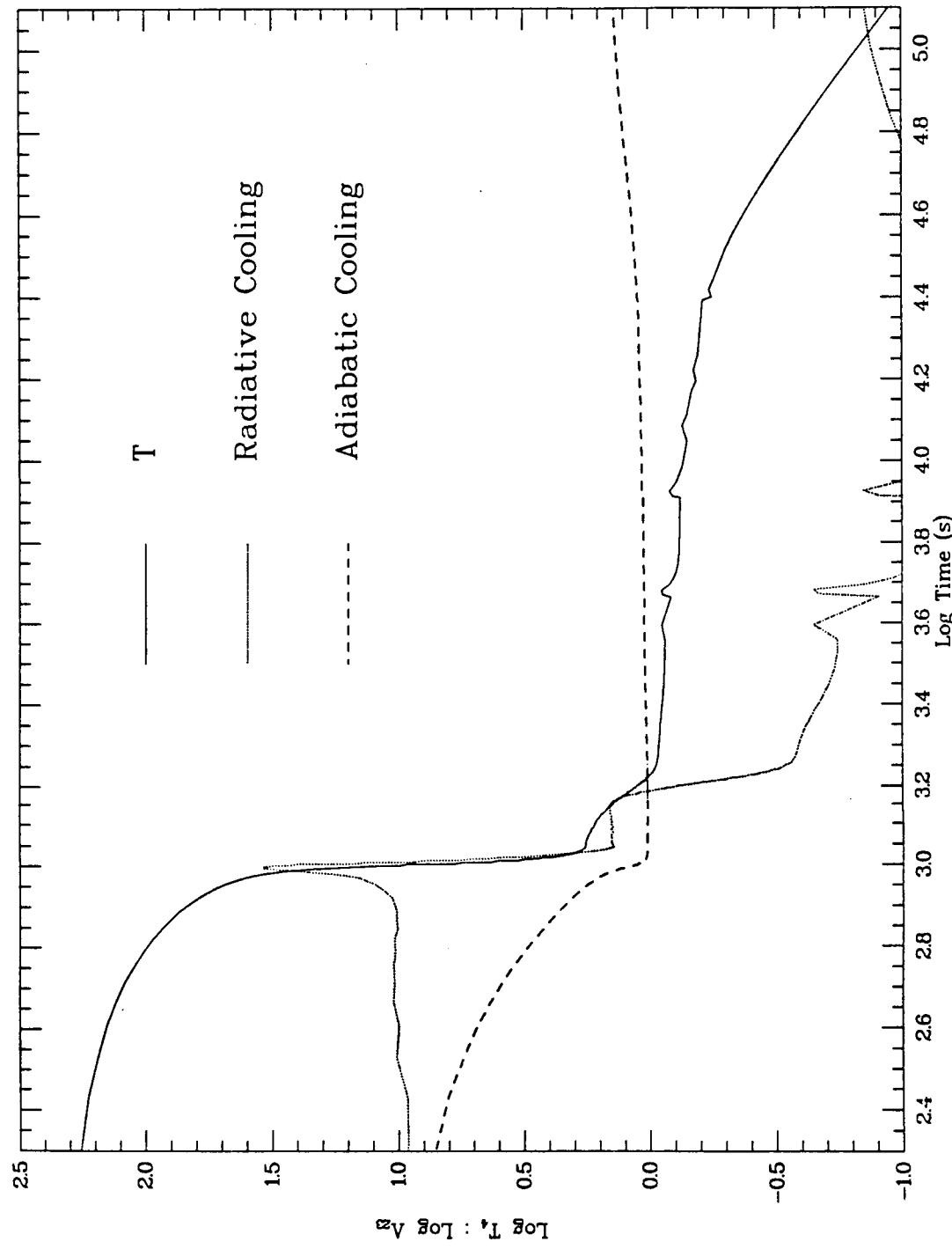


Figure 2 - Structure assumed for the detailed wind-disk shock model, as described in the text.

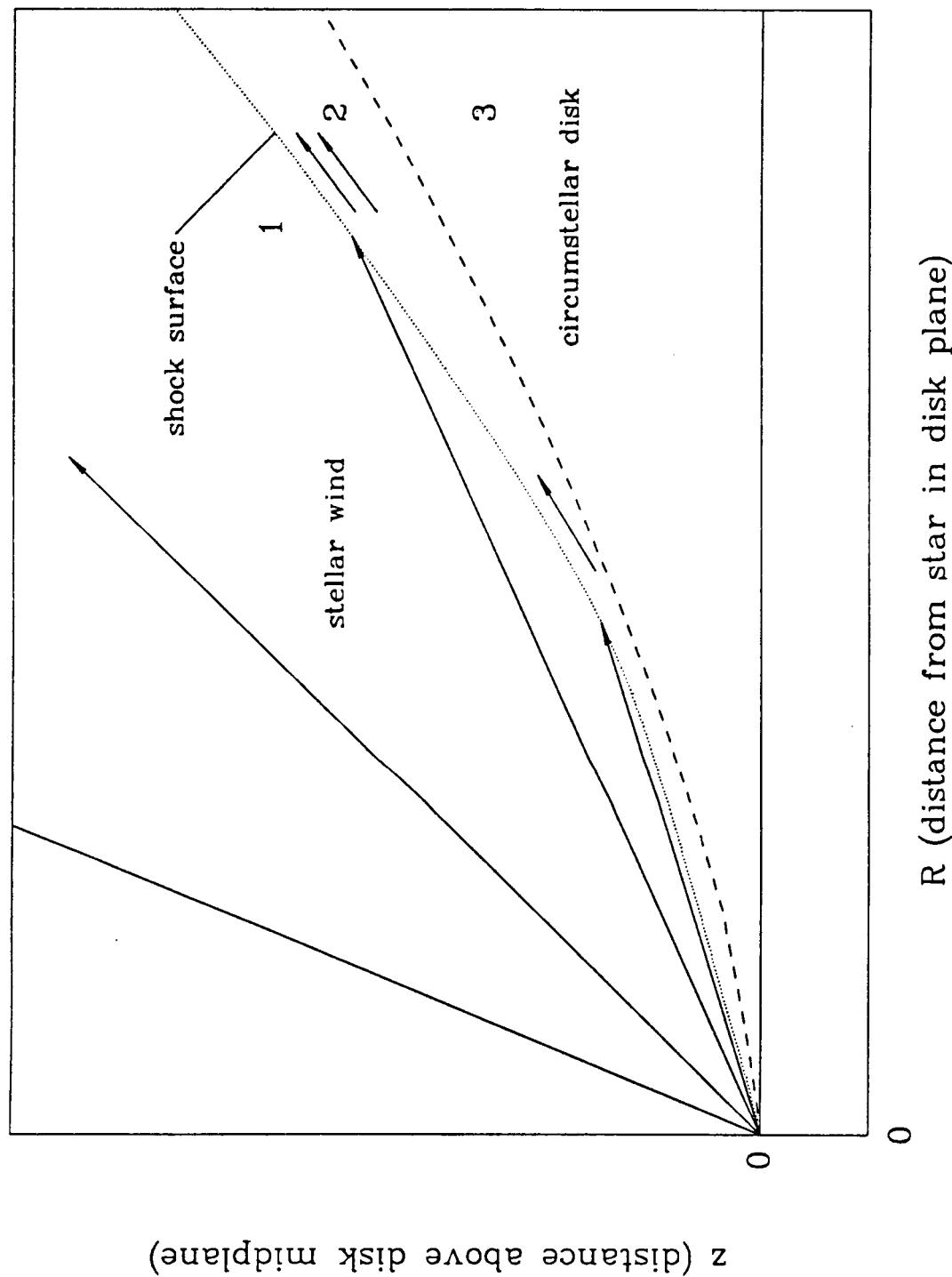


Figure 3 - The location of the wind-disk shock for the model described in the text. The distances are given in units of A.U. The solid line is the basic model, while the dashed line indicates the effect of the Cantó (1980) centrifugal correction. The dotted line is the $z \propto r^{9/8}$ disk photosphere calculated by Kenyon and Hartmann (1987) to reproduce the infrared excess emission of typical T Tauri stars.

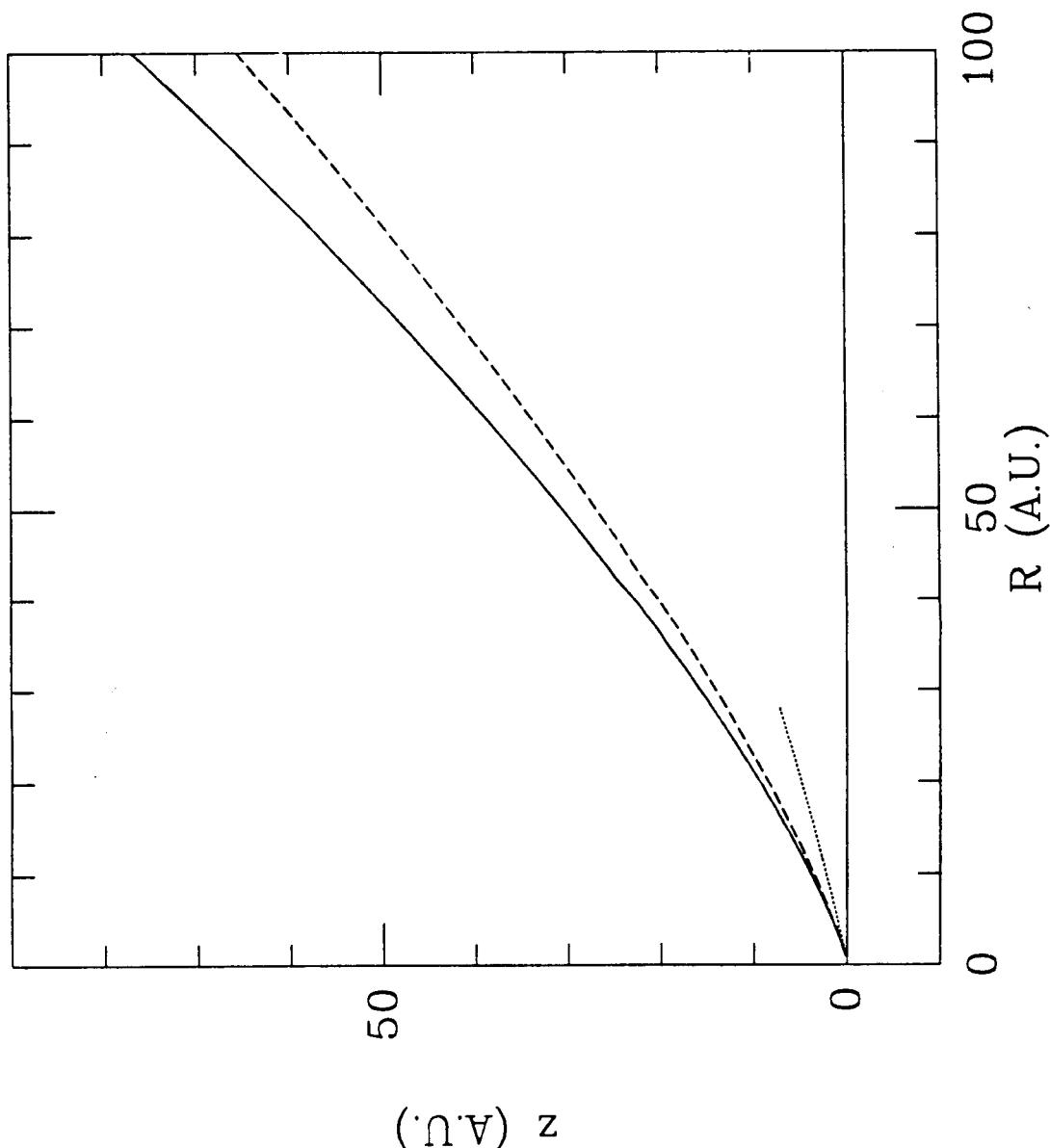


Figure 4 - The shock velocity along the disk model surface shown in Fig. 6. The solid line is the basic model, while the dashed line indicates the effect of the Canto (1980) centrifugal correction. The jog at small radii is due to the approximate nature of the inner boundary conditions used (see text); the solution at large r is insensitive to the exact inner boundary conditions used.

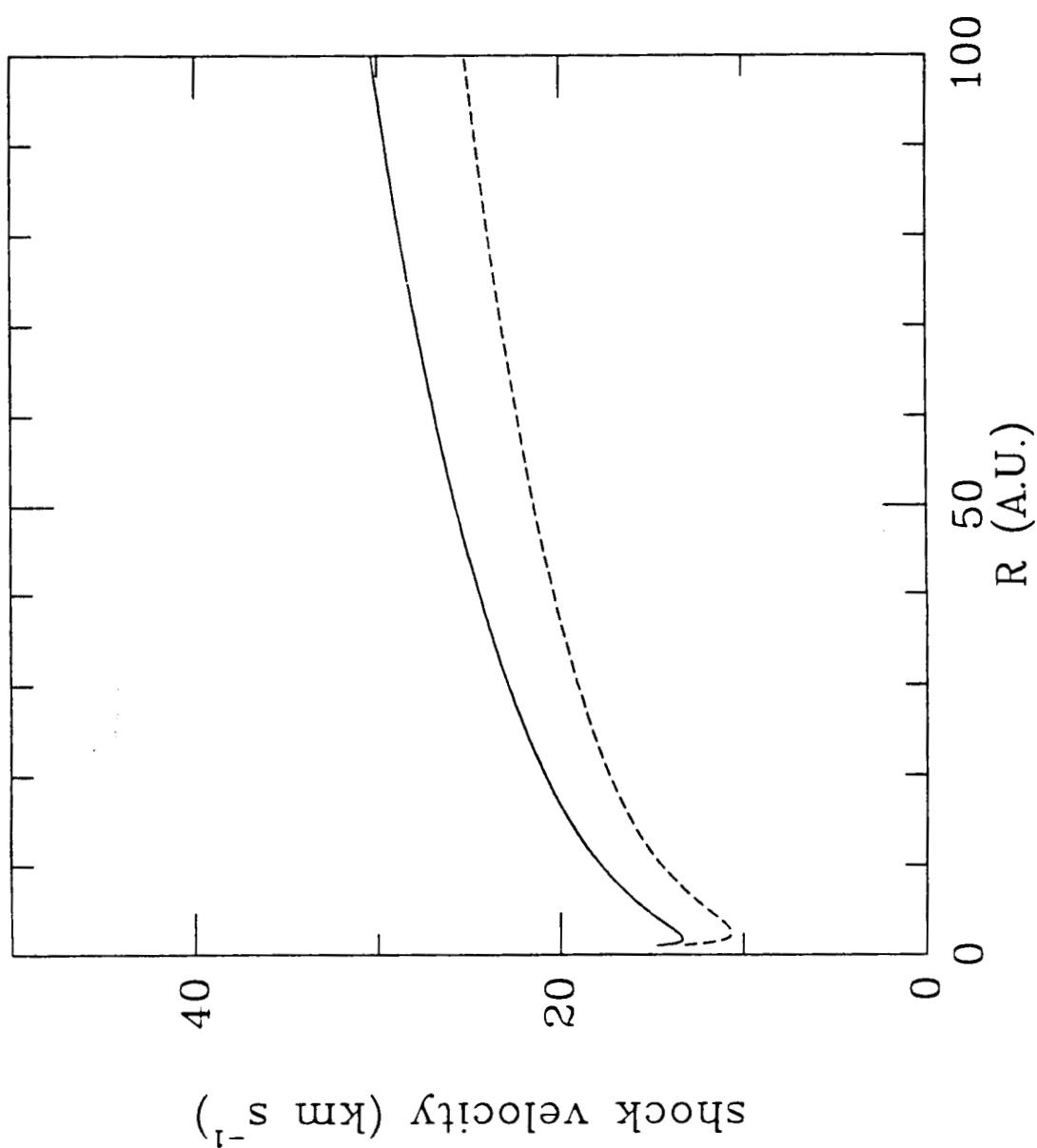


Figure 5 - The forbidden-line emission profiles predicted by the wind-disk shock model of Figs. 6 and 7 (basic model), viewed from an angle 60° from the disk axis.

